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SPECTROSCOPIC DETERMINATION OF ELECTRON TEMPERATURE AND PERCENTAGE IONIZATION IN HELIUM PLASMA

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The spectroscopic diagnostic technique presented for determining electron temperature is a refinement of the method of Cunningham, Frieman, and Harm[1]. In general, the method utilizes the observed excitation cross sections for helium spectral lines that are known over a range of electron energies. The cross sections for a singlet and a triplet line are then averaged over a Maxwellian distribution of electron energies. The ratio of these averaged cross sections is then known as a function of electron temperature, and, hence, the intensity ratio of these spectral lines may be plotted against electron temperature. Thus, the electron temperature may be determined by observing the relative intensities of the indicated spectral lines.

In reference 1, the observed spectral lines were the singlet 2^1P-4^1D(4921 A) transition and the triplet 2^3P-4^3S(4713 A) transition. The cross section data were taken from Lees[2].

The electron temperatures obtained by observing the relative intensities of these transitions may be misleading, however, because of errors inherent in the cross sections.

Gabriel and Heddle[3] have indicated that an error in absolute-intensity calibration exists in Lees' investigation. The relative magnitudes of these cross sections may also be in error, since some values will be enhanced by the effects of secondary processes due to the relatively high pressure (44μ) used in this investigation.

Investigations of excitation cross sections of levels that are affected by secondary processes such as imprisonment of resonance radiation, radiative transfer, and excitation exchange actually yield an apparent excitation cross section that differs from the true electron-excitation cross section. The extent to which these processes effect the cross section determination depends upon the pressure in the collision chamber, and, therefore, the apparent cross section would be expected to vary with pressure. Lin and St. John[4] have shown that this is indeed the case for the 4^1D level as illustrated in Fig. 1. Consequently, the observed intensity ratio of the spectral lines used in reference 1 would vary with pressure, even though the electron temperature were to remain constant.

Since the method presented by Berger[5] for determining the percentage ionized in a helium plasma also utilizes Lees' cross section data and the observation of the 4921 A radiation, it will be subject to these same processes.

In recent experiments, St. John[6] has shown that the excitation cross sections for the 4^1S and 4^3S levels are relatively insensitive to pressure in the range of 0 to 130 microns. On the basis of these results, a spectroscopic diagnostic scheme is presented in which the electron temperature is determined from the observed intensities of the 2^1P-4^1S(5047 A) transition and the 2^3P-4^3S(4713 A) transition, and the percentage ionized is calculated from the relative intensities of the 5047 A neutral line and the 4686 A He II line.

The cross sections used for the neutral lines incorporated the results of a number of previous investigations[7,8,9]. Gabriel and Heddle[3] have corrected for the effects of secondary processes in their investigation of helium cross sections at 108 electron volts. Frost and Phelps[9] point out that Thieme's[7] excitation functions for members of the same series have very nearly the same shape, and that the excitation function of any state may be expressed as the product of a shape function $g_j(V)$ and some magnitude D_j, which may conveniently be taken to be the maximum cross section value. Thieme's[7] experiments were performed at low pressure s ($\cong 5\mu$), and this shape functions for the S states should be close to the true shape functions within the experimental error. The cross sections used in this scheme consist of Thieme's[7] shape functions and a magnitude obtained by fitting Gabriel and Heddle's[3] results at 108 electron volts to these shape functions. Cross sections determined in this manner yield a credible, self-consistent set of helium excitation functions.

The intensity of a j-k transition I_{jk} is given by the relation

$$I_{jk} = N_o N_e Q_{jk}(V)V \qquad (1)$$

where N_o is the neutral density, N_e is the electron density, V is the electron velocity and $Q_{jk}(V)$ is excitation cross section for the j-k transition. If there is a distribution of electron energies, equation (1) becomes

$$I_{jk} = N_o N_e \langle Q_{jk}(V)V \rangle \qquad (2)$$

The brackets indicate a value averaged over the distribution.

Thus, the intensity ratio of the 5047 A line to the 4713 A line x_o is given by

$$x_o = \frac{I_{5047}}{I_{4713}} = \frac{N_oN_e \ \langle Q_{5047}(V)V\rangle}{N_oN_e \ \langle Q_{4713}(V)V\rangle} = \frac{\langle Q_{5047}(V)V\rangle}{\langle Q_{4713}(V)V\rangle} \tag{3}$$

Similarly, the intensity ratio of the 4686 A He II line and the 5047 A He I line x_+ is given by

$$x_+ = \frac{I_{4686}}{I_{5047}} = \frac{N_iN_e \ \langle Q_{4686}(V)V\rangle}{N_oN_e \ \langle Q_{5047}(V)V\rangle} = \frac{N_i \ \langle Q_{4686}(V)V\rangle}{N_o \ \langle Q_{5047}(V)V\rangle} \tag{4}$$

where N_i is the ion density. Letting $F(kT_e) = \dfrac{\langle Q_{4686}(V)V\rangle}{\langle Q_{5047}(V)V\rangle}$ Eq. (4) becomes

$$x_+ = \frac{N_i}{N_o} F(kT_e) \tag{5}$$

From the definition of the percentage ionized P and Eq. (5), it is seen that

$$P = \frac{100 \ N_i}{N_i + N_o} = \frac{100}{1 + \dfrac{F(kT_e)}{x_+}} \tag{6}$$

The excitation functions for the helium neutral lines have been empirically fit with equations that represent the excitation cross section as a function of electron velocity. These equations are then multiplied by the electron velocity and averaged over a Maxwellian distribution to obtain the quantities $\langle Q_{5047}(V)V\rangle$ and $\langle Q_{4713}(V)V\rangle$. The parametric equations and other pertinent data are presented in table I.

In this table, $\beta = \left(\dfrac{m_e}{2kT_e}\right)^{1/2}$, v_m is the velocity corresponding to the threshold energy of the level considered, and v_j is the velocity corresponding to the lower limit of integration in the averaging process.

A comparison of the actual excitation functions and the parametric fits is shown in Fig. 2.

The 4686 A line corresponds to a 4-3 transition in He II. The quantity $\langle Q_{4686}(V)V \rangle$ is taken from Berger[5] who has calculated this cross section by scaling the hydrogen cross sections for exciting the "4" levels and multiplying by the branching ratios of Bethe[10]. The empirical excitation function used by Berger[5] for the hydrogenic cross section asymptotically approaches the Born approximation at large velocities, is in agreement with the experimental evidence that the cross section is zero at the threshold velocity, and exhibits a maximum at approximately twice the threshold velocity.

Now that the averaged cross sections have been computed, the quantities $F(kT_e)$ and x_o are plotted against electron temperature in Fig. 3.

In order to obtain the electron temperature and the percentage ionized, one merely needs to observe the intensity ratio x_o of the indicated neutral lines and obtain the electron temperature and $F(kT_e)$ from Fig. 3. The percentage ionized is then calculated by using the observed x_+ and Eq. (6).

The 4686 A ion line is the least intense of the spectral lines observed. Experimental measurements using conventional recording techniques show that this line is readily observed at ion densities of 10^{10} - 10^{11} ion per cubic centimeter and electron temperatures of 20 electron volts.

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TABLE I. - PARAMETRIC FITS TO EXCITATION FUNCTIONS

Line, A	Parametric $Q(V)$	Range, ev	$\langle Q(V)V \rangle$
5047	$\tau V^2 - A$	$23.67 \leq kT_e \leq 35$	$\frac{2}{\pi^{1/2}} \frac{\exp(-\beta^2 V_m^2)}{\beta} \left[\frac{2\tau}{\beta^2}\left(1 + \beta^2 V_m^2 + \frac{\beta^4 V_m^4}{2}\right) - A(1 + \beta^2 V_m^2)\right]$ where $\tau = 7.359\times10^{-48} \frac{cm^2 - g}{ev}$; $A = 43.48\times10^{-20}\ cm^2$
	$\frac{K}{V^{3/2}}$	$35 \leq kT_e \leq \infty$	$\frac{2}{\pi^{1/2}} \beta^{1/2} K \Gamma_{\beta^2 V_j^2}\left(\frac{5}{4}\right)$, where $K = 9.66\times10^{2}\ cm^2 \left(\frac{ev}{g}\right)^{3/4}$
4713	$\tau V^2 - A$	$23.59 \leq kT_e \leq 28$	$\frac{2}{\pi^{1/2}} \frac{\exp(-\beta^2 V_m^2)}{\beta} \left[\frac{2\tau}{\beta^2}\left(1 + \beta^2 V_m^2 + \frac{\beta^4 V_m^4}{2}\right) - A(1 + \beta^2 V_m^2)\right]$ where $\tau = 34.73\times10^{-48} \frac{cm^2 - g}{ev}$; $A = 179.8\times10^{-20}\ cm^2$
	$\frac{K}{V^4}$	$28 \leq kT \leq \infty$	$-\frac{2}{\pi^{1/2}} \beta^3 K E_i(-\beta^2 V_j^2)$, where $K = 1.27\times10^{-39}\ cm^2 \left(\frac{ev}{g}\right)^2$

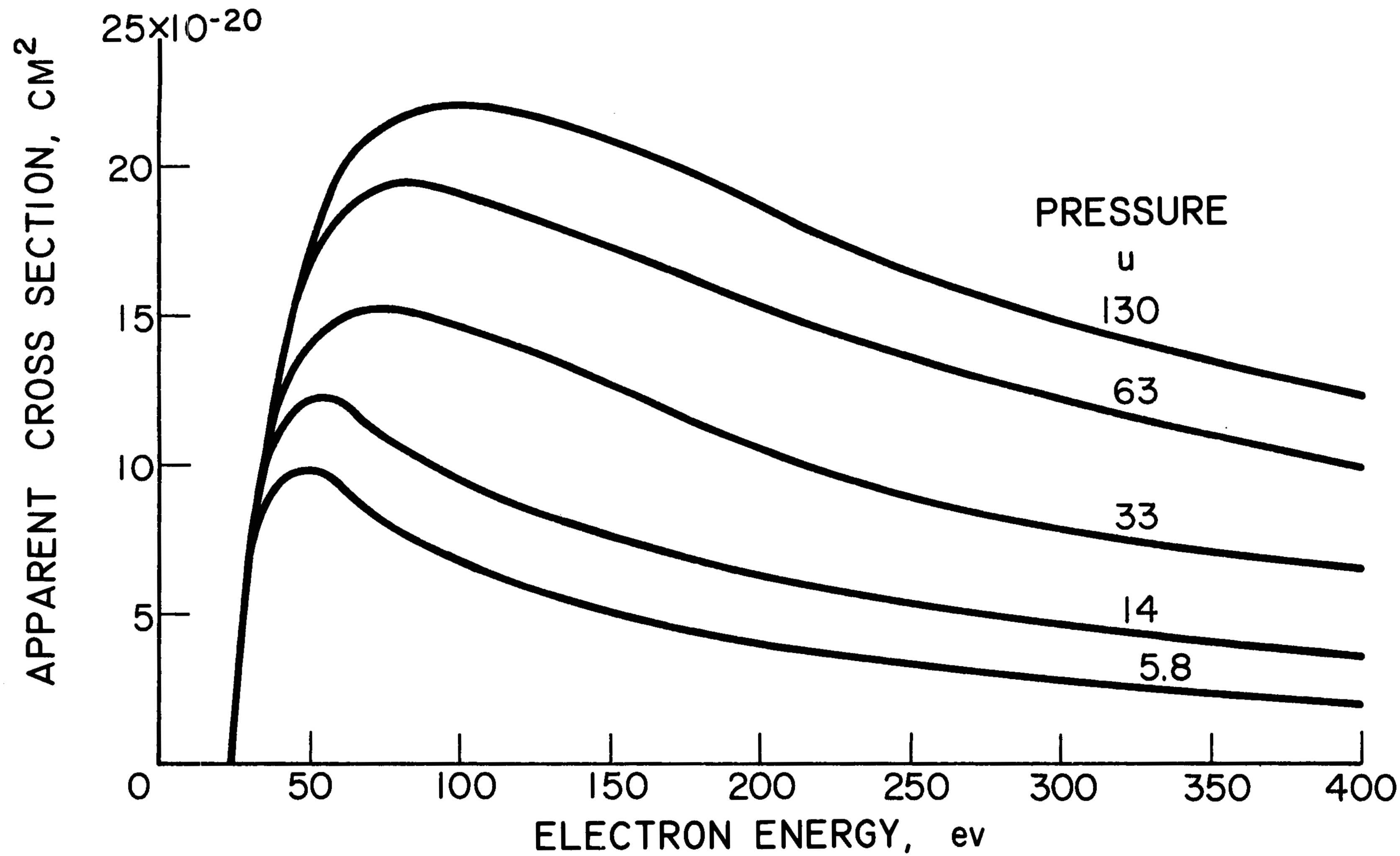

Figure 1. - Variation of 41D apparent excitation function with pressure.

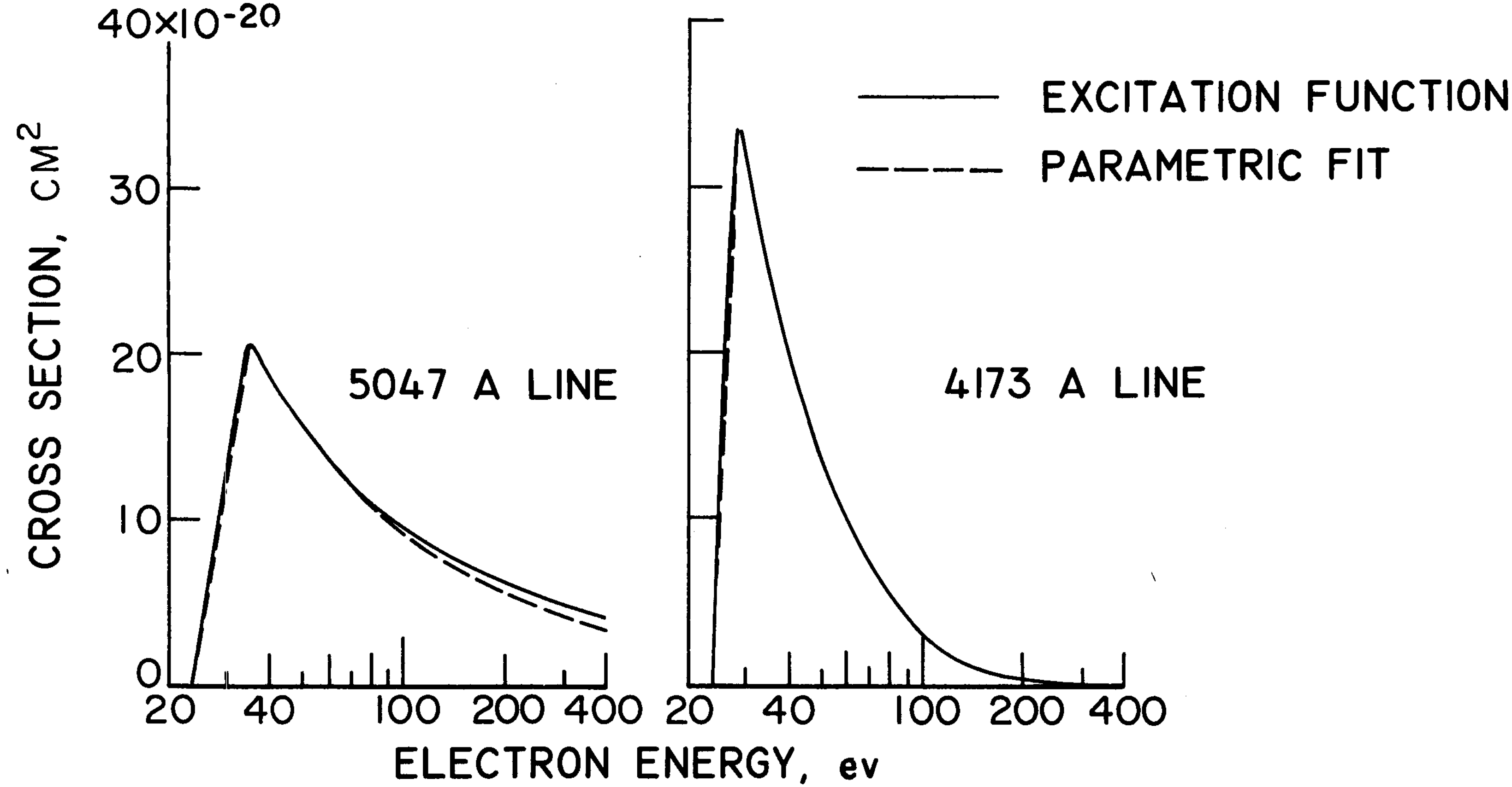

Figure 2. - Comparison of parametric fits and excitation functions.

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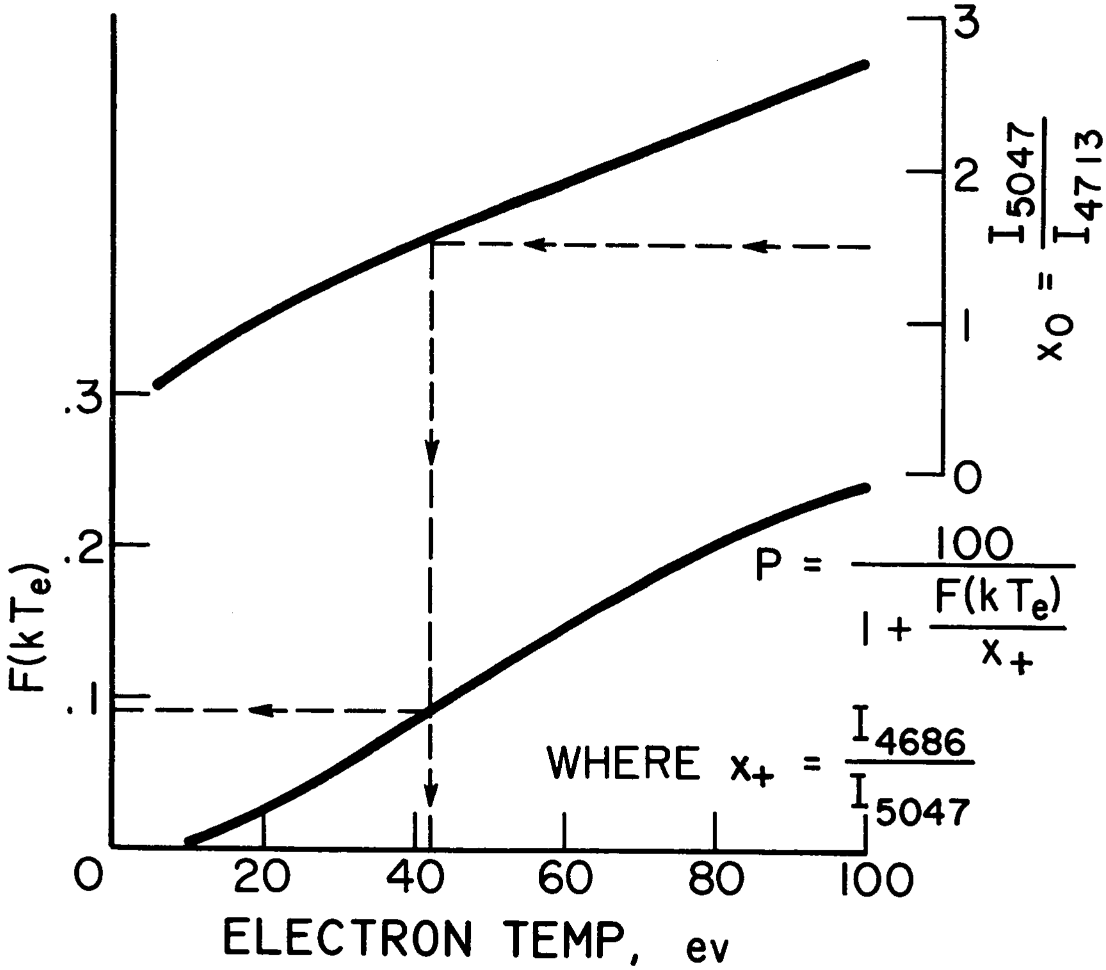

Figure 3. - Variation of X_0 and $F(kT_e)$ with electron temperature.